

A neutrino interaction with two vertices topology detected by OPERA

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The OPERA experiment has reported the detection of five ν_τ candidates in the CNGS ν_μ beam, allowing to reject the background-only hypothesis at the 5.1σ level. Besides these events, on May 23rd 2011, OPERA detected a “neutral current like” interaction with two secondary vertices. Such topologies mainly arise from Charged Current interactions of a ν_τ with associated charm quark production or from Neutral Current interactions of a ν_μ with production of a charm anti-charm pair. These topologies have generally low probabilities. A dedicated multivariate analysis is in progress to allow discriminating between these two hypotheses. Here the event topology is described in detail and preliminary results of the classifiers for all possible contributions are given.

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1 The OPERA experiment

The OPERA (Oscillation Project with Emulsion tRacking Apparatus) experiment has searched for neutrino oscillations over a baseline of 730 km. The experiment was exposed to the CNGS high energy neutrino beam (mean $E_{\nu_\mu} \sim 17$ GeV) optimized for the appearance of ν_τ from a pure beam of ν_μ [1]. OPERA was a modular detector composed of two Super Modules (SM) each being composed of a target region followed by a muon spectrometer. The basic unit of the target was the so-called “brick”, an array of 57 nuclear emulsion layers interleaved with 56 1 mm thick lead layers; its transverse size was 12.5×10.2 cm² and the thickness was about 10 radiation lengths [2]. Nuclear emulsion have a sub-micrometric spatial resolution which grants the precise reconstruction of the neutrino interaction inside the target, as well as the associated short-lived particles like the τ lepton. An OPERA film has 2 emulsion layers (each 44 μ m thick) on both sides of a transparent triacetylcellulose base (205 μ m thick). The overall target mass was 1.25 kton, composed of about 150000 bricks. Each brick is a stand-alone device which allows momentum measurement through Multiple Coulomb Scattering (MCS) in the lead plates [3], and electromagnetic shower energy reconstruction. The target region was instrumented with plastic scintillator strips [4], used to localize the neutrino interactions point; providing the probability map of the bricks where the interaction might have taken place. The muon spectrometers were equipped with Resistive Plate Chambers and drift tube detectors. The design leads to a muon momentum resolution better than 30% for momenta up to 25 GeV/c. Thanks to the high signal to background ratio the ν_τ search was done on an event by event basis [5]. This possibility also relies on the excellent spatial resolution of nuclear emulsions and on the good knowledge of the expected decay topologies; having the capability to identify anomalous impact parameters (IP) of particle tracks with respect to the reconstructed primary interaction vertex. This is the trigger for the τ lepton decay signal. The charm decay dataset is used as a proxy to validate the reconstruction method, because of the similarity decay topologies. Further background suppression is achieved by applying kinematical selections.

OPERA has reported the detection of five ν_τ candidates, allowing to reject the background-only hypothesis at the 5.1σ level [6].

2 Description of the double-vertex event

Event 1114301850 occurred in the first SM with no associated muon track (“0 μ -event” [7]). The total hadronic energy is ~ 20 GeV. A scheme of the event is shown in Fig. 1. A primary stopping point was located in the lead layer between emulsion films 31 and 32, and a secondary one at plate 33. The upstream vertex is composed of 5 tracks; the downstream vertex has one prong kink topology. The five tracks are not compatible with a single vertex (IPs are larger than the standard threshold $\geq 10\mu$ m). By minimizing the IP the most probable event topology is composed of two vertices: a primary one (V_I) in Figure 1 is 581.8 μ m upstream with respect to the top emulsion layer of plate 32; while the secondary one (V_{II}) is 102.6 μ m downstream with respect to V_I . V_I is formed of tracks 2, 4 and 5, while V_{II} is defined by tracks 1 and 3. IPs of all tracks with respect to both vertices are listed in Tab. 1. The distance between the primary and secondary vertices is 103.2 μ m.

Track 4 makes a (95 ± 17) mrad kink (537.6 ± 174) μ m upstream of plate 33; the

Track ID	Single Vertex IP (μm)	Two vertices IP (μm)	
		w.r.t. V_I	w.r.t. V_{II}
1	8.3	36.2	0.1
2	8.8	1.0	6.5
3	4.8	25.9	0.1
4	13.0	1.5	20.4
5	5.1	2.2	9.6

Table 1: Impact Parameters evaluated assuming a topology of a single vertex, or two vertices.

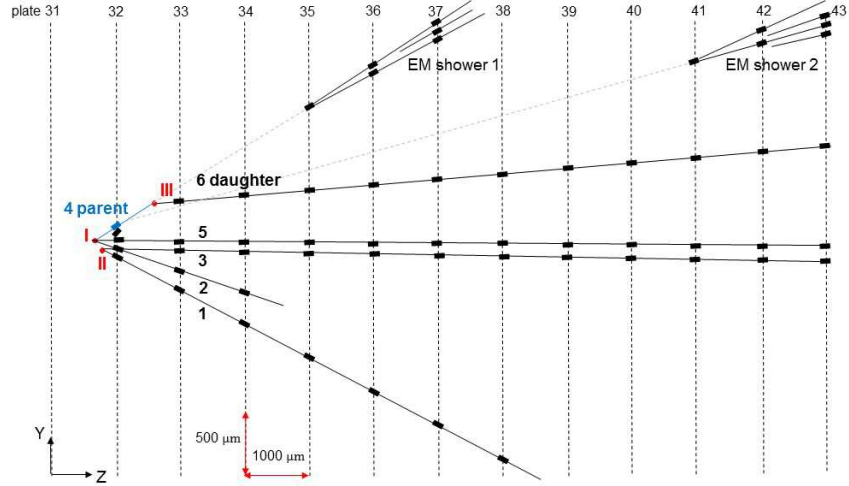


Figure 1: Event projection in the yz plane. Base-tracks are represented with segments, while volume tracks with lines; the blue one represents the daughter particle. Vertices are shown with red dots; EM showers 1 and 2 are also indicated

minimum distance between this track “parent” and track 6 “daughter” is $(0.9 \pm 2.9) \mu\text{m}$; the parent flight length is $(1174 \pm 74) \mu\text{m}$. The kink point is labelled V_{III} . Track 2 is composed off 3 base-tracks (segments measured in three consecutive plates) and stops at plate 34; due to the short length its momentum, equal to $(0.31 \pm 0.08) \text{ GeV}/c$, was evaluated considering absorption processes in lead [8]. Track 3 shows a re-interaction at plate 53 (not shown), while tracks 1 and 5 traverse the whole brick.

The momentum of tracks 1, 3, 5, and 6 was estimated by the MCS method, yielding $2.1^{+1.6}_{-3.1} \text{ GeV}/c$, $4.3^{+3.1}_{-7.1} \text{ GeV}/c$, $0.54^{+0.45}_{-0.68} \text{ GeV}/c$ and $2.7^{+2.1}_{-3.7} \text{ GeV}/c$ respectively (the quoted interval is the 68% C.L.).

Two electromagnetic (EM) showers were identified at plates 35 and 41. Their estimated energies are $E_1 = (7.2 \pm 1.7) \text{ GeV}$ and $E_2 = (5.3 \pm 2.2) \text{ GeV}$, respectively. These photons could arise from one or two π^0 . The two π^0 hypothesis is highly disfavoured because a second pair of EM showers was not found; by minimizing their IPs both photons are assumed emerging from vertex V_{III} $(8 \pm 8) \mu\text{m}$ and $(40 \pm 11) \mu\text{m}$. An extensive search for nuclear fragments was performed and no fragments were detected in any of the three vertices. Both topology and kinematics were confirmed by measurements using an independent scanning system.

In the OPERA proposal the observation probability of such a topology was taken as negligible, therefore no reconstruction procedure had been designed. Applying the standard selection criteria, none of the primary vertex tracks can be classified as a τ lepton. In particular the minimum daughter transverse momentum should be at least 300 MeV/c, while the best fit value for the parent is 242 MeV/c. Processes which could produce two short decays (within ~ 1 mm) are:

1. ν_τ CC interaction with charm production
2. ν_μ NC interaction with $c\bar{c}$ pair production.
3. other possibilities require a re-interaction of a final state particle in the lead; or a short decay of a semi-stable particle (π , K) within few millimetres from the primary vertex.

Hadron re-interactions could mimic any of these possibilities:

- ν_τ CC interaction with hadron re-interaction
- ν_μ NC interaction with two hadron re-interactions
- ν_μ CC interaction with single charm production, with one hadron re-interaction and a misidentified muon
- ν_μ CC interaction with two hadron re-interactions and a misidentified muon.

3 Analysis of the event

An analysis was performed using classifying algorithms to distinguish among decay and hadronic interaction topologies, and therefore classify the observed event (section 2). The analysis is being finalized and here only classification results are presented without an estimate of the significance of the observation.

About 250 millions neutrino interaction events were generated using the GENIE [9], and HERWIG [10] (charm pair channel) generators. The simulation includes: ν_μ CC DIS; ν_μ NC DIS; and ν_τ CC DIS interactions. All cases were simulated with and without charm production. The generation was done using fixed neutrino energies, then re-weighted considering the CNGS neutrino flux and the relative cross section of each process. Propagation through the OPERA brick was done with the GEANT4 framework [11], taking into account the experimental angular acceptance of reconstructed tracks in the OPERA emulsions and hadronic re-interactions inside the brick. Brick finding, vertex location, momentum reconstruction and muon identification efficiencies were taken into account using data driven parametrizations.

Only events with the same topology as the observed one were considered *i.e.* no muon, electron or positron reconstructed at the primary vertex, one kink (one prong) secondary vertex with a charged daughter not reconstructed as a muon, and a two prong secondary vertex. Therefore, an event is defined as *signal* when a τ plus a charm particle are selected by the topology cuts; while as *background* in case of a double vertex topology without an identified τ particle. A set of twelve variables (topologic and kinematical) are used for the classification, namely: the daughter momentum and transverse momentum; the kink angle between parent and daughter; the charged and neutral parents flight length; the invariant mass; the total EM energy; the transverse angle φ among tracks of the one and two prongs vertices; angle between charged and neutral parents; the missing transverse momentum at primary; and the hadronic momentum of tracks of the primary vertex, discarding tracks which belongs to a secondary vertex; the scalar sum of momentum of tracks of the neutral decay vertex.

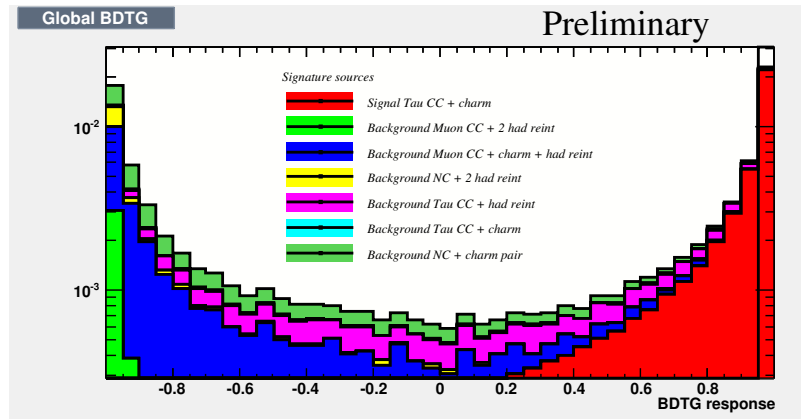


Figure 2: BDTG classifier output, considering signal and several background-like channels. The vertical black line represents the preliminary BDTG classification of the measured event.

In the analysis three types of classifiers were used. A Multi Layer Perceptron flavour of an Artificial Neural Network; two different kinds of a Boosted Decision Tree classifier, an Adaptive Boost and the Gradient Boost (BDTG). These are trees of binary choices taken on one single variable at a time until a stop criterion is fulfilled. With respect to the Adaptive Boost, the latter is more stable with respect to outliers which can occur by chance in any distribution, especially heavy-tailed distribution. Finally a Fisher discriminant was used [12]. Figure 2 shows the preliminary output of the BDTG classifier, where the τ plus charm topology is peaked at 1; the contribution of all the other considered channels is also plotted. The black line is the output evaluated using event 1114301850.

4 Conclusions

An event with two secondary vertices was measured by OPERA. A preliminary classification based in a multi-variate analysis, shows that this event turns to be likely a ν_τ CC interaction with an associated charm production. Future perspectives of the analysis include the evaluation of the number of expected events for each considered channel, and therefore obtain the significance of the observation. The analysis is in progress and a more comprehensive description will be given in a future publication which is in preparation.

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